SIMULATIONS OF THE ION-HOSE INSTABILITY FOR DARHT-II LONG-PULSE EXPERIMENTS

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Abstract

Computer simulations of the ion-hose effect typically use Particle-In-Cell (PIC) computer codes or codes using the spread-mass model. PIC simulations, though offering more reliable results, require extensive running time on large computers. In order to support commissioning experiments in the DARHT-II induction linac at Los Alamos National Laboratory, we have improved a spread-mass code so that we can survey quickly the parameter space for the experiment. In this paper, we describe the code modifications and the benchmarking against a PIC code, and present results of our simulations for the DARHT-II commissioning experiment.

INTRODUCTION

During Phase-II commissioning of the DARHT (Dual-Axis Radiographic Hydrodynamics Test) Facility [1], beam physics tests (also known as Long-Pulse Experiments, LPE) will focus on the stability of the 2-μs beam pulse against beam-breakup and ion-hose effects. The goal is to demonstrate that beam-breakup and ion-hose instabilities will not cause the DARHT-II beam to become unacceptable for radiographic uses.

The ion-hose instability was studied previously for the DARHT-II induction linac using computer simulations including Particle-In-Cell (PIC) and Spread-Mass (SM) methods [2, 3]. PIC simulations, though offering more reliable results, require extensive running time in large computers. Our goal is to improve a SM simulation code, which has a typical running time of a few minutes, so that it can be used to give fast and reasonably reliable guidance during commissioning.

In this paper, we will describe modifications to the SM code. Numerical results obtained using the improved SM model are compared to PIC simulations to assess the accuracy of the SM simulations. Then we will describe SM simulation results for LPE of Phase-II commissioning.

IMPROVED SPREAD-MASS SIMULATION CODE

Previously, SM simulations for DARHT assumed beam and accelerator parameters that were uniform along the length of the accelerator. These parameters include the solenoidal magnetic field, beam energy, and beam radius. To improve the SM simulations, we modified the SM code to include these parameters as a function of longitudinal distance along the accelerator (z). We also included the effect of the radial magnetic field due to the varying longitudinal magnetic field. This latter effect will introduce a rotation of the beam centroid around the accelerator axis.

Our SM code was based on the SM code written by Genoni with uniform accelerator parameters. Our development and solution of the equations follows closely that by Genoni in Ref. [2], which in turn was a generalization of the original ion-hose SM formulation by Buchanan in Ref [4]. Since details of Genoni's work can be found in Ref. [2], we will highlight here only the new modifications.

Equation (1) in Ref. [2], which considers only the linear ion-hose force, was modified by adding the effect of the radial magnetic field by including a third term on the left-hand side of the equation, i.e.

$$\frac{\partial^2 b}{\partial z^2} = -k_{\beta e}^2 (b-d) + ik_{ce}\frac{\partial b}{\partial z} - ik_{ce}\left(\frac{B_r}{rB_z}\right) b \qquad (1)$$

where b and d, respectively, are the beam and ion-channel centroid-displacements from the axis. In the third term, B_r and B_z are the radial and longitudinal components of the solenoidal magnetic fields and r is the radial position of the beam. Equation (2) in Ref. [2] remains unchanged, i.e.

$$\frac{\partial^2 d}{\partial \tau^2} = -\omega_{\beta i}^2 (d-b) - i\omega_{ci}\frac{\partial d}{\partial \tau} \qquad (2)$$

In equations (1) and (2), $k_{\beta e}^2$ and $\omega_{\beta i}^2$ are given as:

$$k_{\beta e}^2 = \frac{f\nu}{\gamma R^2} \quad and \quad \omega_{\beta i}^2 = \frac{m_e \nu c^2}{m_i R^2}$$

where m_e and m_i are the electron and ion masses, γ is the electron relativistic factor, $\nu = {}^{eI_b}\!/_{m_e c^3}$, $\tau = t - {}^{z}\!/_{c}$, I_b is the beam current and f is the fractional neutralization. k_{ce} and ω_{ci} are defined as:

$$k_{ce} = \frac{eB_z}{\gamma m_e c^2} \quad and \quad \omega_{ci} = \frac{eB_z}{m_i c}$$

Equations (1) and (2) were further transformed by adding the SM formulation and nonlinearity as in Ref. [2], arriving at equations similar to equations (27) and (28) in Ref. [2]. These equations were then solved numerically with the solenoidal magnetic field, beam energy, and beam radius as functions of z .

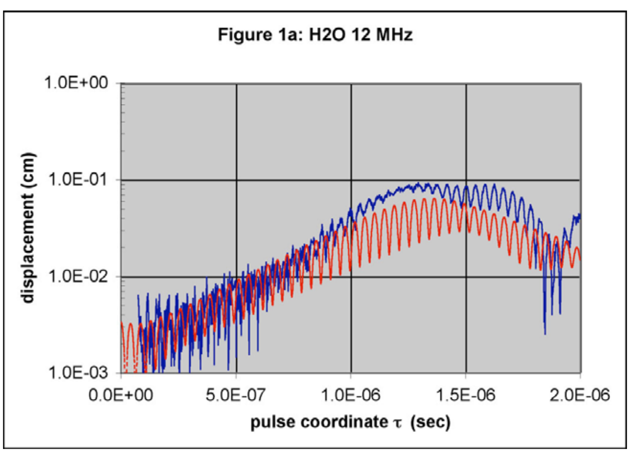
BENCHMARKING OF SM SIMULATIONS

We benchmarked our SM code against results obtained using LSP, a 3-D PIC code from ATK-MRC [5]. Four cases were compared: a) H_2O gas excited with a 12-MHz input beam displacement oscillation; b) H_2O gas excited by a broadband beam displacement oscillation; c) Ar gas excited with an 8.4-MHz input beam displacement oscillation; and d) Ar gas excited by a broadband beam displacement oscillation. The frequencies of 12 and 8.4 MHz were chosen because they were the estimated ion-hose resonance frequencies. The broadband oscillation spectrum is represented by a sum of 100 sinusoidal oscillations with discrete frequencies distributed uniformly over a frequency range from 0 to 60 MHz. Both SM and PIC simulations used same initial displacements and accelerator parameters for Phase I Commissioning as listed in the 'Benchmark' column in Table 1.

Table 1: Accelerator parameters used for the benchmark and LPE simulations

Parameters	Benchmark	LPE
Accelerator length (cm)	2250	2750
Initial Beam Energy (MV)	4.2	3.1
Final beam Energy (MeV)	11.34	8.1
Average rms beam radius (mm)	7.2	5.5
Average Bz (Gauss)	700	625
Gas pressure (torr)	$1\text{x}10^{-6}$	$0.1\text{-}1 \text{ x } 10^{-6}$

Typical PIC and SM results are shown in Figures 1a and 1b, respectively, for cases (a) and (c). The beam displacements are plotted as a function of time (τ) measured back from the head of the pulse. Some general conclusions can be drawn. PIC and SM results show good qualitative agreement. The SM results have more pronounced oscillations. Agreement is better for single-frequency excitation, probably due to differences in random excitations used for the broadband cases. With the results of the four benchmark cases, we conclude that the SM simulations can predict the ion-hose excitations to better than a factor of two and are lower than the PIC results.



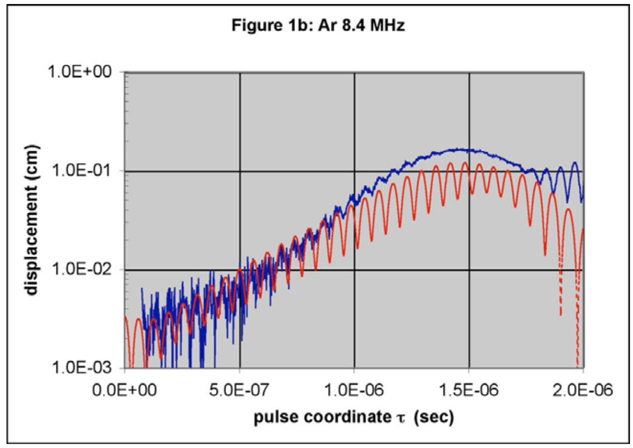


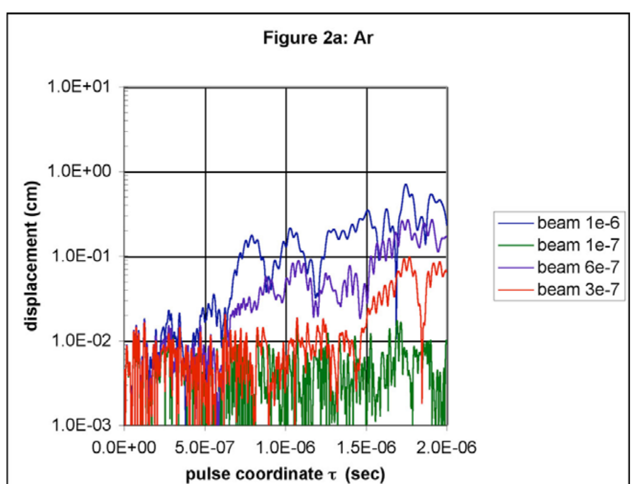
Figure 1: Comparison of LSP (blue) and SM (red) results for benchmark cases (a) and (c) are shown, respectively, in Figure 1a and 1b.

SPREAD-MASS RESULTS FOR PHASE-II COMMISSIONING

The plan for LPE is to observe ion-hose effects using some of the following gases: H_2O, Ar, Kr, Xe, or N_2 in a pressure range of $1 \text{ x } 10^{-7}$ to $1 \text{ x } 10^{-6}$ torr. The relevant accelerator parameters are summarized in Table 1.

Using the improved SM code, we obtained results for the LPE assuming a broadband excitation. The broadband excitation was represented by a sum of sinusoidal oscillations at 100 discrete frequencies equally spaced between 0 and 50 MHz. The initial amplitudes of these oscillations were 0.001 cm.

Typical results are shown in Fig. 2 for gases (a) Ar and (b) Xe, respectively. The beam displacements along the pulse were plotted for four different pressure levels in the beam pipe. To summarize the results of beam displacement as a function of pressure, we have plotted in Fig. 3 the average beam displacements of the last quarter of the beam pulse (between 1.5 and 2.0 μs) as a function of pressure for different gases. Results show the instability growth with increasing pressure levels and towards the back of the pulse.



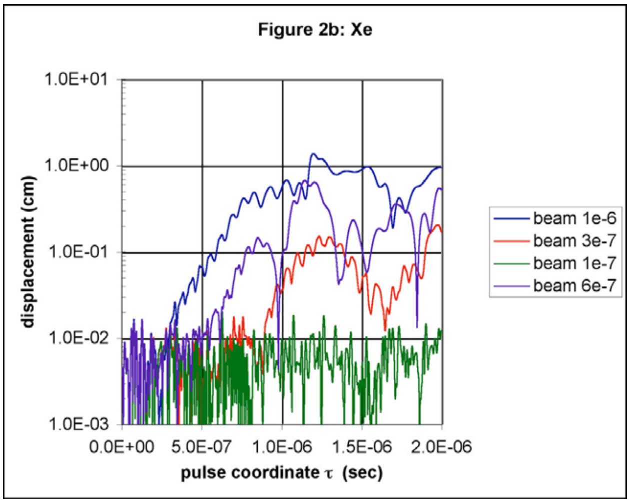


Figure 2: Typical results for (a) Ar and (b) Xe, showing the beam displacements along the beam pulse for different pressures.

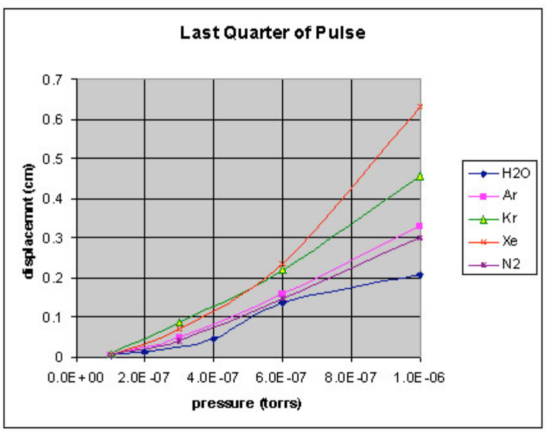


Figure 3: Average beam displacements for the last quarter of the beam pulse as a function of pressure for different gases.

The runtime for each run using the SM code was less than 15 minutes. We found that good results could be obtained when the time and z resolutions used in integrating equations (1) and (2) were, respectively, 2 cm and 1 ns, or better. The SM code is presently configured to read the z-dependent parameters from a file, which, in our runs, is produced with a beam envelope code (XTR) routinely used at DARHT. Other needed inputs are entered interactively while the code is running so that cases with different parameter values can be tried.

SUMMARY

Simulation results of ion-hose effects were obtained for different gases in support of Phase II commissioning of DARHT II induction linac. The results were obtained with a computer code using the spread-mass model. This code was designed to give quick results to support commissioning. It differs from other spread-mass codes in that it includes the z dependence of accelerator parameters. Results from this code compare well with the more reliable results obtained using time-consuming 3-D Particle-In-Cell simulations.

ACKNOWLEDGEMENT

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